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Improving the performance of composite floors subjected to post-earthquake fire

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Abstract

It is well-known that tensile membrane action in concrete floor slabs can enhance the fire resistance of a composite steel frame building. Vertical supports provided by protected beams along the edge of the slab panel play an important role in the development of the tensile membrane actions. The present study investigates the effect of fire insulation delamination on the protected beam, as might occur in an earthquake, on the fire resistance of composite floors subject to fire following an earthquake. The results show that fire insulation delamination considerably reduces the development of tensile membrane action. Based on the results obtained, two methods of improvement are presented to enhance the development of tensile membrane action concurrent with fire insulation delamination. It is found that increasing slab thickness and improving fire protection rating can enhance the fire resistance of the whole building even with fire insulation delamination.

Keywords: *tensile membrane action, fire engineering, fire insulation, composite building, post-earthquake fire*

1. Introduction

Fire following an earthquake is one of the potential multi-hazard scenarios to be considered in the design of new and management of existing structures. Building characteristics and the presence of services such as gas, electricity etc. can combine to increase the risk of fire following seismic action. The combined fire and earthquake hazard has gained attention recently in an effort to improve structural resilience under multi-hazard events. Existing studies have shown that post-earthquake fire events cause many fatalities and high levels of damage [1]. As an example, fire following the 1995 Kobe earthquake destroyed 7000 buildings[2]. Thus, substantial new research work is required to address the challenge posed by post-earthquake fire events.

Steel structures are widely used in seismic regions due to the number of advantages they offer including being lightweight and possessing high ductility. To maintain stability and integrity of steel structures during a fire, fire insulation such as sprayed fire resistive material (SFRM) is commonly applied on the surface of the steelwork. The main role of fire insulation is to delay the temperature rise of the steel during a fire. Past events have demonstrated that earthquakes can cause fires in buildings, damage active fire protection systems such as sprinklers, and reduce the effectiveness of fire-fighting capability. Thus, fire insulation can play a critical role in mitigating the effect of the post-earthquake fire on the building structure.

SFRM is often used as fire insulation since it offers many advantages such as low thermal conductivity and cost-effectiveness. In current practice, the fire behaviour of a steel structure is evaluated with the assumption that the SFRM is perfectly intact during fire following an earthquake. However, there is a high possibility that the role of SFRM can be compromised if the SFRM gets detached from the steel surface during an earthquake. Both experimental and field observations have shown that SFRM delamination can occur under static and dynamic load situations [3–5]. Such delamination can jeopardize the performance of steel structures during fire.

Significant research has been conducted on the behaviour steel frames subject to fire following earthquake induced ground motion [6–10]. However, there is still a lack of detailed research on the effect of earthquake damages on the development of tensile membrane action. In a previous study by the authors[10], the effect of earthquake damage on a composite steel frame in fire was examined. Two types of earthquake damage, fire insulation delamination and residual deformation, were investigated separately. For the particular frame and seismic characteristics investigated, the results showed that fire insulation delamination on the steel beams had a greater effect on the beam deflections. Based on this finding, using the same frame characteristics, the present study investigates the consequences of fire insulation delamination on the protected beam in regards to the tensile membrane action mechanism of the composite slab under fire conditions. This load carrying mechanism is known from many studies (e.g.[11,12]) on undamaged composite structures to be key in ensuring resilience to fire, hence it is of value to know its mechanics and role in earthquake damaged structures. The aim of this investigation is to propose the most effective and practical ways to enhance fire resistance of composite floors where localised insulation delamination has occurred. Towards this, the effect of slab characteristics and the nature of the remaining fire insulation are examined for the first time in a 3D numerical study.

2. Composite building design

In the most common and conventional fire safety design, the fire resistance of steel framed buildings has been estimated by standard fire tests on isolated elements supported statically determinately [13]. In reality, structures do not behave as isolated individual elements. When an individual steel element loses strength and stiffness, in many cases the load will be transferred to other parts of a structure, i.e. load carrying mechanisms change. Therefore, the actual response of buildings cannot be assessed by the conventional approach. A clear example of this sort of behaviour seen in real structures was observed during the UK's Cardington fire tests [11,14]. These tests indicated that tensile membrane action in concrete floor slabs of steel-concrete composite buildings can improve the fire resistance substantially beyond that which might be assumed from single element tests. Tensile membrane action develops when the slabs undergo large vertical displacements. As can be seen in Figure 1, tensile membrane action occurs in a two-way spanning slab when the induced radial tension in the centre of the slab is balanced by a peripheral ring of compression [15].

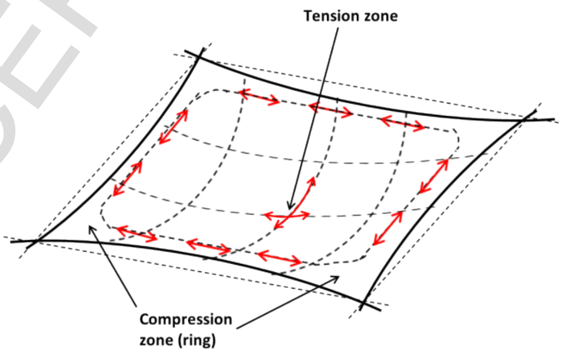


Figure 1: Tensile membrane action mechanism [15]

When tensile membrane action is considered in the design, the composite slabs need to be divided into slab panels. The internal secondary beams can be left unprotected, and the supporting beams around the perimeter of the slab panel are protected so that they can support the vertical load without plastic hinges forming. Vertical support can practically be maintained by protecting beams around the perimeter of slab panel to incur a temperature less than 620°C at the required fire resistance time [16].

Allowing for tensile membrane action in design can significantly reduce the need for fire protection of steel beams. Hence, it is not surprising that many studies have been conducted on the influence of tensile membrane action on the fire resistance of composite steel frame buildings. Lamont et al. [12] compared the fire behaviour of composite buildings when fire protection is applied to only edge beams and when no beams are fire protected. It was found that when external beams are protected, the slab tends to span in two directions owing to sufficient support from the tensile membrane action mechanism. In contrast, when no beams are protected, the slab tends to span in one direction in a manner similar to beams in catenary action.

Huang et al. [17] conducted a series of analyses to investigate the effect of tensile membrane action in the composite slab using different patterns of fire protection for the steel beams. The study showed that it is possible to leave a number of the beams unprotected due to the beneficial effect of tensile membrane action. The analyses also demonstrated that the surrounding cool structure can improve the fire resistance of the fire compartment. Lin et al. [18] investigated the effect of protected beams on the fire resistance of composite buildings. They compared the behaviour of the composite floor with fixed and non-fixed vertical support on the protected steel beams at the perimeter of the slab panel. The results showed that non-fixed vertical support significantly reduced the development of tensile membrane action. In comparison to the case with fixed support, tensile membrane action was fully mobilised.

Jian and Li [19] investigated parameters affecting tensile membrane action of reinforced concrete floors in fire. It was found that failure modes of the slab depend on reinforcement layout, aspect ratio and boundary condition. Nguyen and Tan [20] conducted experiments on three one quarter scale composite slabs with different bending stiffnesses of protected edge beams under fire conditions. The results showed that an increase of the edge beam bending stiffness initially reduced the deflection. At higher temperature, the effect of greater stiffness of the edge beams was negligible.

All of the aforementioned studies confirmed that protected edge beams have a significant effect on the fire resistance of the structure. However, these studies mainly assumed that vertical support along the perimeter of the slab panel was provided by fully protected beams. Fire insulation delamination on the protected beam may occur in an earthquake and increase vertical deflection in the protected beams under fire conditions[10]. This can influence the ability of a structure to develop tensile membrane action. Accordingly, the present study presents the consequence of fire insulation delamination on the protected beam along the edge of slab panels under fire conditions. Moreover, the effects of protection type and concrete type with the view to improving the fire resistance of composite slab are investigated. Thus, the main aims of this study are:

- To investigate the effect of fire insulation delamination on the protected beam and the effect on the development of tensile membrane action in steel-concrete composite buildings.
- To undertake a parametric study to investigate methods that may be used to improve the performance of these types of buildings in fire when fire insulation delamination has occurred.

A series of numerical analyses of three-dimensional composite buildings are carried out in which the effects of fire insulation delamination are investigated. Two sets of analyses are performed. In the first set of analyses the consequences of fire insulation delamination are studied. In the second set of analyses, two methods of improvement namely the use of lightweight concrete and enhancements of the fire resistance rating, are presented to enhance the performance of the building when fire insulation delamination has occurred.

3. Numerical modelling of a composite steel frame building

In this study, the general purpose finite element software ABAQUS [21] was employed to analyse the generic composite frame building. Steel beams and columns were modelled using 1-D line elements (B31), while concrete slabs were modelled using 4-noded shell elements (S4R). Rebar layers were specified in the shell elements to represent the steel mesh in the concrete slabs. The interaction between the steel beams and the concrete slab is assumed to be fully composite. A tie constraint was applied to represent full composite action between steel beams and concrete slabs. An existing study by Zolghadr-Jahromi et al. [22] has shown that partial composite interaction has negligible effects on the global response of 3D frames, therefore this was not considered in the present study. The steel beam-to-column and beam-to-beam connections were assumed to be fixed and pinned respectively for simplicity. Fixed and pinned connections were modelled using the joint-rotation connector available in ABAQUS. It is worth noting that changing pinned connection to fixed has little effect on modelling results since the connection will change from fixed to pinned as a result of heating[23]. Connection failure is not considered in this study. A non-linear static analysis using a modified Newton-Raphson solver was adopted since it is less time consuming and provides more readily interpreted results than dynamic analyses. Many previous analyses of heated composite structures (e.g.[11,24]) have shown the validity of this approach.

Elastic-perfectly plastic structural steel behaviour was assumed for both columns and beams, and temperature-dependant properties for steel were adopted according to Eurocode EN 1993-1-2[25]. For concrete, a damaged plasticity model was implemented in ABAQUS[21]. The default values of parameters used to define the damaged plasticity model are: dilatation angle = 40°; eccentricity = 0.1; the ratio of equibiaxial compressive yield stress to uniaxial compressive yield stress, f_{b0}/f_{c0} = 1.16; the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian, K = 0.667; and viscosity parameter = 0. The uniaxial concrete material behaviour at ambient and elevated temperature was taken as defined by Eurocode EN 1992-1-2[26].

A validation was carried out using existing experimental and previous analytical work to confirm the model approach used in this study. A simplified composite steel frame from the Cardington tests [27] previously analysed by Gillie [28] was selected (See Figure 2). The Young's modulus and yield strength of the steel beams and columns was 210 GPa and 300 MPa respectively. The compressive strength of concrete in the slabs was taken as 47 MPa, and yield strength of rebar was 450 MPa. The concrete slab thickness was 130 mm. The rebar mesh consists of 6-mm diameter bars at 200-mm centres each way and the rebar was located at the mid-depth of slab. The thermal expansion of steel and concrete was taken as 1.35×10^{-5} °C^{-1} and 9×10^{-6} °C^{-1}, respectively. The concrete and steel material properties at elevated temperatures follow the recommendations in Eurocode EN 1992-1-2[26] and Eurocode EN 1993-1-2[25].

A total load of 5.48 kN/m^2 is applied all over the concrete slab and temperature loadings were applied on only the shaded area shown in Figure 2. The secondary beam was heated up to 800°C, while the concrete slab was heated up to 600°C at the lower surface slab with a linear gradient of

4.6C/mm. Then the structure was cooled to ambient temperature. Figure 3 plots the predicted deflection at mid-span of the heated beam versus temperature. The plots show that the deflections obtained in the present model are in good agreement with existing experimental and previous analytical studies.

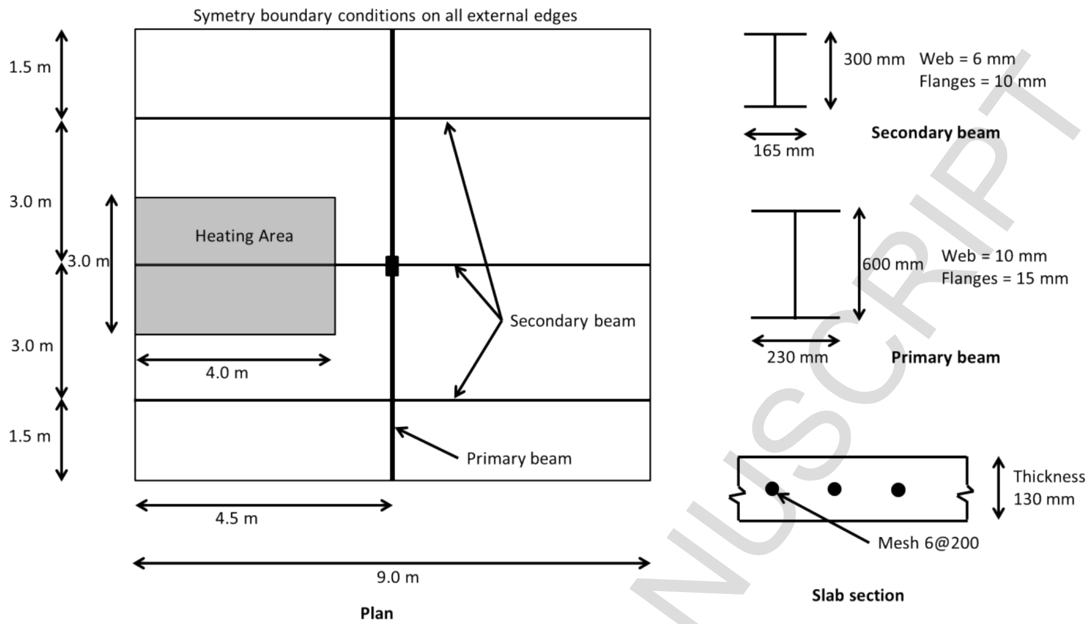


Figure 2: Geometry of simplified version of the first Cardington test [28]

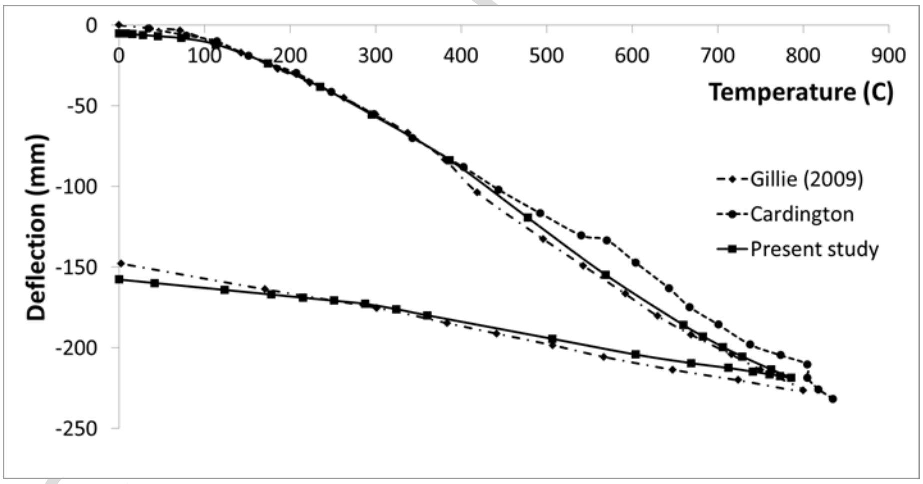


Figure 3: Comparison of mid-span beam deflections

4. Generic frame

A generic five-storey office composite steel frame building is analysed in this study. Figure 4 shows the plan of the building. The building was designed for high seismicity using a steel moment resisting frame with medium ductility according to the following Eurocodes; EN 1993-1-1 [29], EN 1994-1-1 [30] and EN 1998-1-1 [31]. A column size of UKC356x127x39 was adopted, while

UKB457x191x74 and UKB356x127x39 sections were used for primary beam and secondary beams, respectively. All columns, primary beams and secondary beams on the main gridlines were protected with a 10 mm thickness of lightweight insulating material which has thermal conductivity of 0.2 W/mK, specific heat of 1100 J/kgK and density of 300 kg/m^3. Other secondary beams were left unprotected, as is common in modern performance-based composite frame design to utilise tensile membrane action.

The S355 steel used for both columns and beams has an ambient temperature yield stress and Young's modulus of 355 MPa and 210GPa, respectively. A floor slab incorporating normal weight concrete with overall depth of 130 mm is used. A rebar mesh is located in the middle of the concrete slab and consists of 6 mm diameter bars at 200 mm centres each way. The compressive strength of the concrete is 45 MPa and the yield strength of the rebar is 450 MPa. Thermal expansion of steel and concrete are taken as 1.35×10^{-5} °C^{-1} and 13×10^{-6} °C^{-1}, respectively. The steel and concrete properties at elevated temperature were adopted in accordance with Eurocodes EN 1993-1-2 [25] and EN 1992-1-2 [26]. The total design load at the fire limit state is taken as 5.5 kN/m^2. This load level results in a load ratio for the primary beams and secondary beams of 0.5 and 0.6 respectively.

The three-dimensional composite building frame is modelled as shown in Figure 5. A mesh size of 0.5m x 0.5m is used for the first floor slab and a mesh size of 1.0m x 1.0m is used for the upper slabs to save the computing cost. Eight elements are meshed for all columns and 18 elements for the beams.

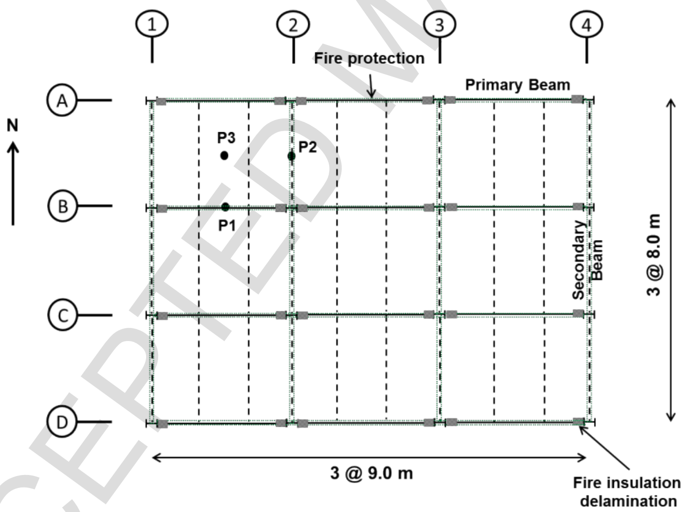


Figure 4: Plan view of generic composite floor

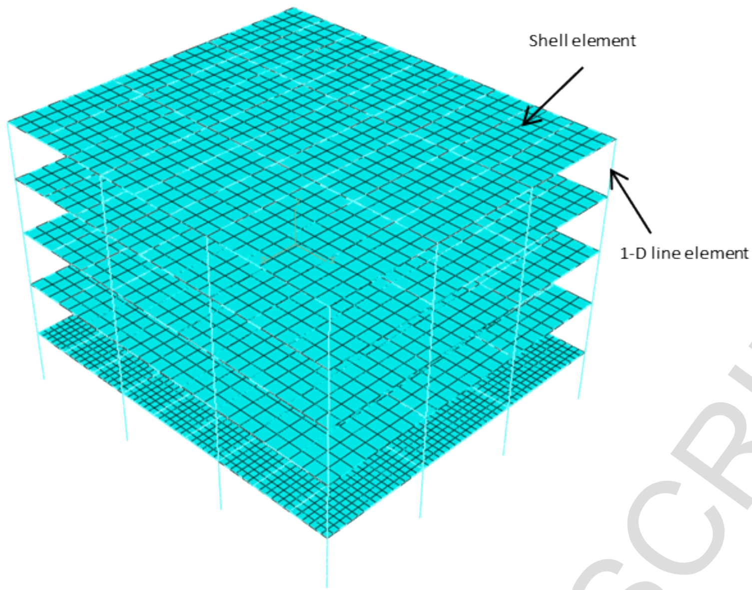


Figure 5: Finite element mesh of the generic frame

A Standard Fire ISO 834 [32] and a Natural Fire were adopted to simulate the fire event. The Natural fire was determined according to EN 1991-1-2 [33]. The fire load of 511 MJ/m^2 was used according to Annex E of EN 1991-1-2 [33], which is for office buildings. The ventilation factor and thermal inertia of compartments are taken as 0.06 $m^{1/2}$ and 1470 $Ws^{0.5}/m^2K$ respectively. The purpose of using a Natural Fire is to study the behaviour of the structure during the cooling phase of a fire, and to give a comparison against the (widely used but unrealistic) Standard Fire. Only one floor (ground floor) which is assumed to have the worst earthquake damage scenario was investigated in this study.

Since in modern buildings open-plan offices are the most common, full-floor compartments were considered and the hot gases were assumed uniform in the fire compartment. The procedure in Eurocode EN 1993-1-2 [25] was adopted to calculate the steel temperatures and a numerical heat transfer analysis using finite element analysis was used to calculate concrete slab temperatures through the thickness. Figure 6 shows the temperatures of both steel and concrete against time under the Standard Fire and the Natural Fire.

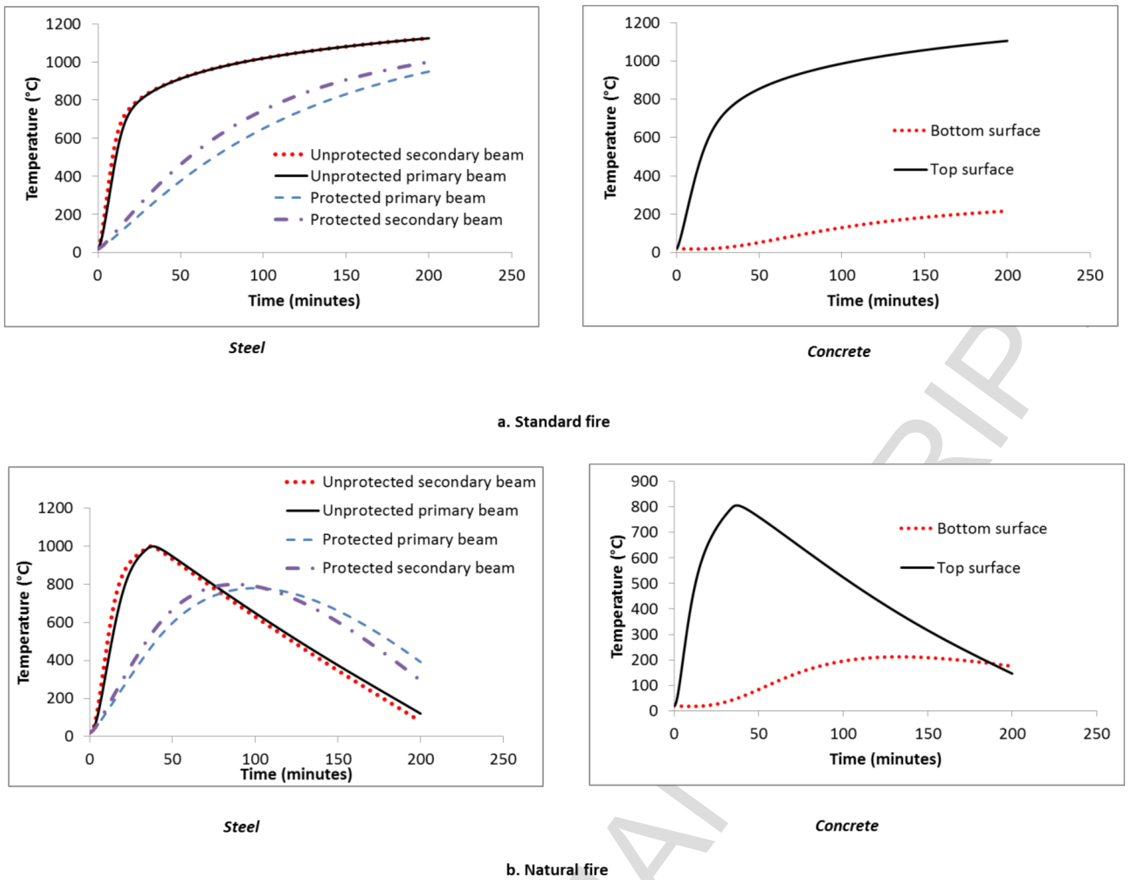


Figure 6: Structural temperature

To determine failure of the slab, an appropriate failure criterion is required. Abu et al. [16] proposed three deflection limits to check failure limit state: a maximum deflection of span/20, TSLAB by the Steel Construction Institute (CSI)[34] and Bailey method limit[35]. Jian and Li[19] found that it is more reasonable to apply a limit of span/20 to predict the failure of the slab even though the slab may experience larger deflection without collapse. Moreover, the limit of span/20 is considered to guarantee the structural integrity and safety of the firefighter. Thus, the limit of span/20 is used in the present study.

5. Results and discussion

5.1 Development of tensile membrane action on undamaged composite floor

This section explains the development of membrane action on the composite floor without fire insulation delamination. Figure 7 shows the vertical deflection of the concrete slab at positions P1, P2 and P3 against time and unprotected secondary beam temperatures under Standard Fire and Natural Fire. As shown in Figure 2, P1 and P2 are located in the mid-span of the protected primary beam and protected secondary beam respectively while P3 is located at the centre of the slab panel.

As seen in Figure 7, the mid-span deflection (P3) reaches the limit of span/20 after 120 minutes (ISO standard fire). At this point, the deflections at P1 and P2 are relatively small. Hence, the tensile membrane action is still fully developed and the slab bends into a bowl-like shape indicative of predominant 2-way action (See Figure 8a). Similar structural behaviour can be observed under the Natural fire. Small deflections at P1 and P2 are noticed up to where unprotected secondary beam temperatures reach 900°C. During the cooling phase, the deflections still increase and slightly exceed the limit after 90 minutes. This is expected because at the cooling phase, the protected beam and slab temperature is still relatively high.

It also can be observed that the mid-span deflection can reach larger than the limit without collapse. However, with increasing temperature, the tensile membrane action is considerably reduced. This is because the vertical support for the floor slab panels is significantly reduced when the deflection at mid-span of the protected beam P1 increases. Once the temperatures of the unprotected beam reach 1000°C, a rapid increase in deflection rate at P1 is identified as the perimeter protected beams lose their strength and stiffness. On the other hand, there is substantial reduction in deflection rate at P2 as the load is predominantly distributed to P1 (one-way). Therefore, a single curvature slab-bending mechanism will develop as indicated in Figure 8b, and potentially lead to a catenary-type failure.

Figure 9 shows the distribution of steel reinforcement stress in the concrete slab. The dark colour refers to compression, while the others relate to tension. It can be seen that the tensile membrane action occurs within the centre of each slab panel as the compressive ring forms around the perimeter of each panel as shown in Figure 9a. When temperature increases further, the tensile membrane action mechanism considerably reduces as compressive rings vanish (see Figure 9b).

This study demonstrates that the vertical deflection of protected beams at the perimeter of slab panels has significant influence on the formation of tensile membrane action. Load carrying mechanism relying on tensile membrane action is stronger than reliant on the catenary action. The tensile membrane action assembles load carrying capacity of slab in compression to provide lateral restraint against slab folding up. On the other hand, catenary action needs some other lateral restraint to prevent collapse.

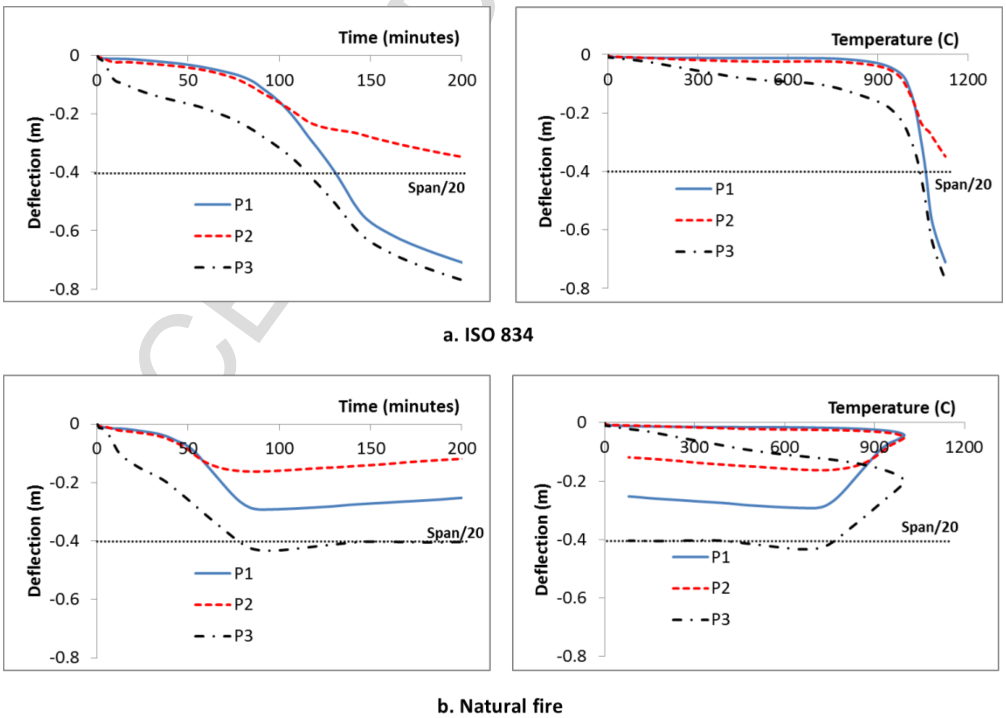


Figure 7: Vertical deflection at position P1, P2 and P3

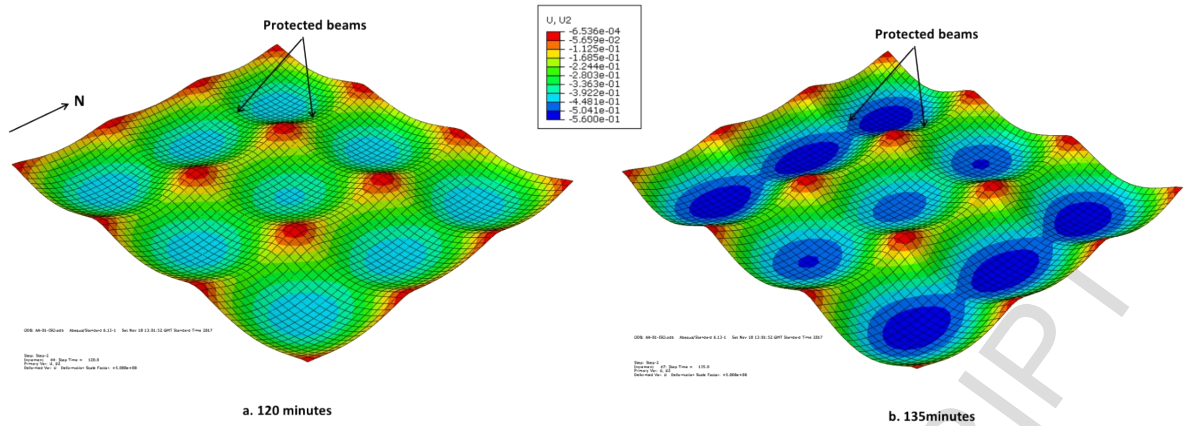


Figure 8: Deflected slab contour exposed to ISO standard fire (units in m)

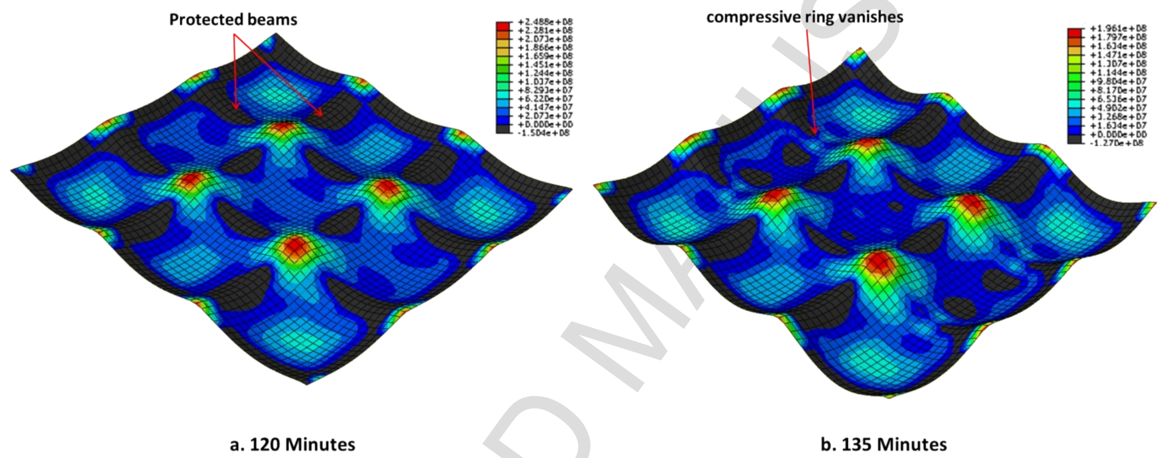


Figure 9: Maximum in-plane stress in the steel reinforcement layer for the slab exposed to ISO standard fire (units in N/m^2)

5.2 Effect of Fire insulation delamination

In this section, the effect of fire insulation delamination is investigated. As previously mentioned earthquake actions may result in damage to a steel structure's fire insulation via delamination. It is apparent that when fire insulation delamination occurs, residual deformation may exist as a result of plastic deformation. Thus, the combined effect of fire insulation delamination and residual deformation could be considered. In order to isolate the effect of delamination itself, residual damage from plastic deformations have not been considered here. As noted earlier, a recent study by the authors [6] on the same composite frame examined here showed that residual deformation from the adopted seismic action has little influence on the fire resistance of the structure, particularly for beams. To account for fire insulation delamination in the present study, the steel beams are assumed unprotected (and hence subject to high temperatures) in the delamination regions. The length of delamination is assumed to be 0.5 m from the face of the column (See Figure 10).

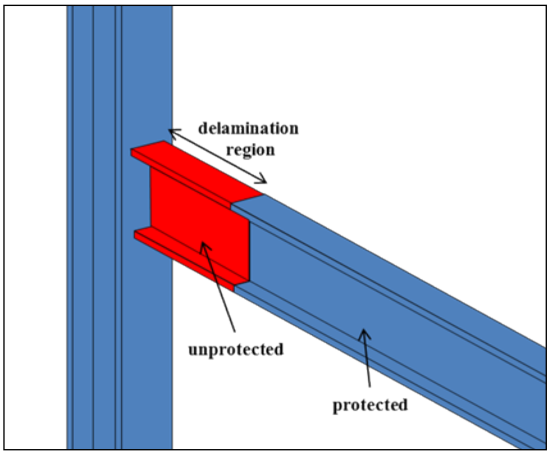
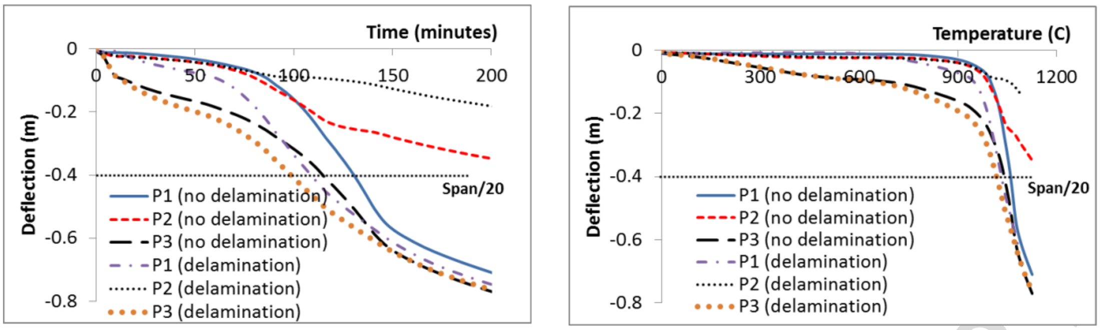


Figure 10: Fire insulation delamination on the protected beam

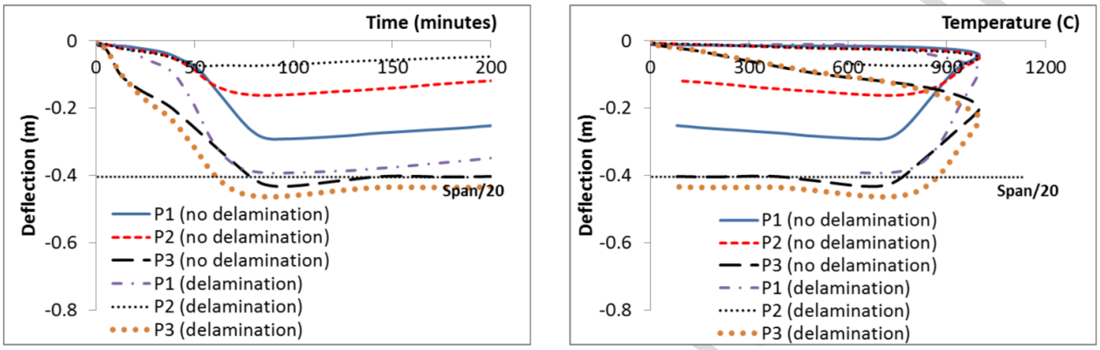
Figure 11 shows the predicted deflections at position P1, P2 and P3 under Standard fire and Natural fire when fire insulation delamination has occurred. It can be observed that the effect of fire insulation delamination is negligible, up to 400°C. But beyond 400°C, there is a sudden increase in deflection because the steel beams at delamination regions rapidly lose strength and stiffness. However, at high temperature, fire insulation delamination has a relatively small effect due to prolonged high temperatures overwhelming the fire protection. It can be seen that the fire insulation delamination reduces failure time from 120 minutes to 100 minutes when exposed to standard fire.

Figure 12 shows deflection slab contour at failure point under ISO standard fire with and without fire insulation delamination. For the case without fire insulation delamination (Figure 12a), the deflections of perimeter beams (P1 and P2) are relatively small. Thus, the tensile membrane action can be fully developed as explained in the previous section. On the contrary, fire insulation delamination results in significantly larger deflections of P1 than in the no-damage case. Therefore, the tensile membrane action mechanism is considerably reduced as shown in Figure 12b. Comparison of the steel reinforcement stress distribution (Figure 13) also clearly shows the effect of fire insulation delamination on the development of tensile membrane action. It can be seen that the compressive rings vanish due to excessive deflection in the protected beam with delamination. This phenomenon changes the load transfer mechanism from two-way into one-way slab behaviour.

This study demonstrates that localised fire insulation delamination can significantly accelerate the reduction of the tensile membrane action mechanism and therefore increases the likelihood of failure of the composite building due to catenary action of the beams. In this case, the benefit of tensile membrane action cannot be assumed in design.



a. ISO 834



b. Natural fire

Figure 11: Predicted deflection at different positions with fire insulation delamination on the protected primary beam

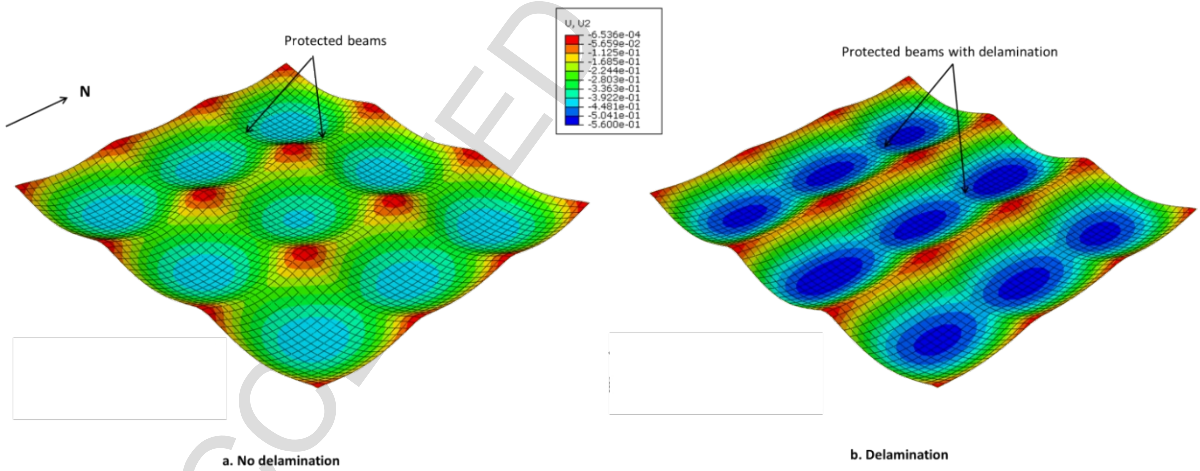


Figure 12: Deflected slab contour with and without fire insulation delamination at failure point exposed to ISO standard fire (units in m)

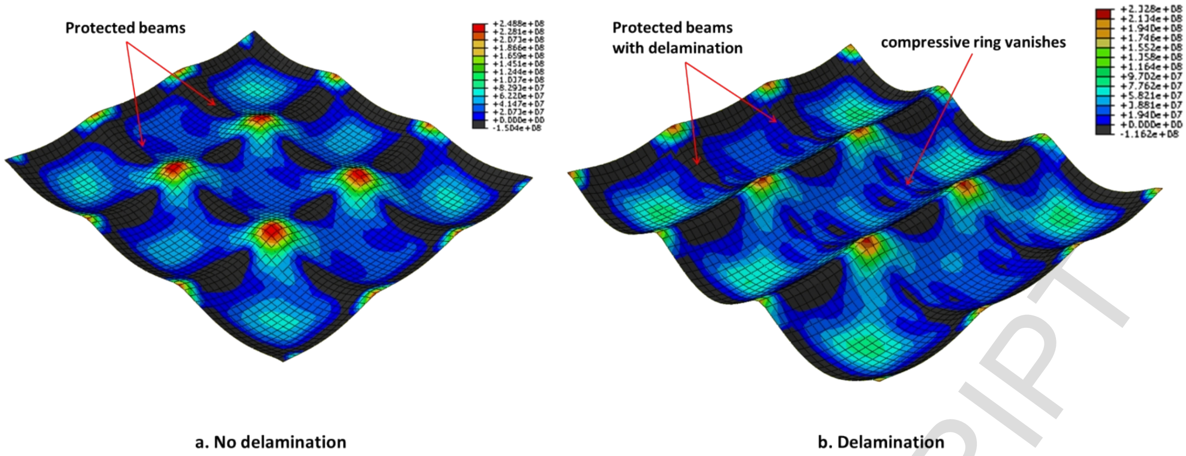


Figure 13: Maximum in-plane stress in the steel reinforcement layer for the slab with and without fire insulation delamination at failure point exposed to ISO standard fire (units in N/m²)

6. Methods of improving fire performance of composite floors

This section presents the results of a parametric study on methods of improving the fire performance of composite floors when fire insulation delamination has occurred. Two different methods have been considered. First, the slabs were replaced by lightweight concrete (LC). Secondly, the fire protection rating was improved to reduce the maximum temperature at protected beams. This study investigates how the methods affect structural behaviour of the composite floor under fire conditions. The consideration of the methods is discussed in the following section.

6.1 Using lightweight concrete

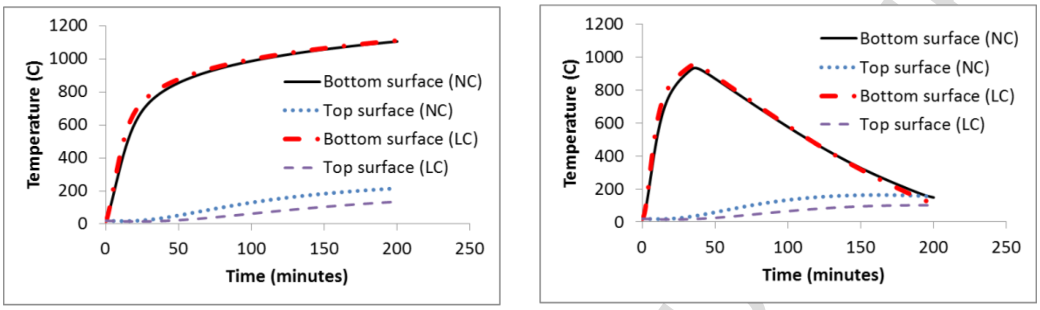
In order to improve fire performance of the composite building, the type of concrete slab i.e. normal weight concrete (NC), was changed to lightweight concrete (LC) slabs. Apart from reducing self-weight load in the structures, lightweight concrete also provides advantages in fire safety design. Lightweight concrete has better thermal stability, lower thermal conductivity and lower thermal expansion compared to normal concrete. This is because its main coarse aggregate is usually a high temperature sintering product which produces more holes inside the aggregate [36,37].

Two thicknesses of LC slabs, 130 mm and 150mm, are considered in this study. First, a slab thickness of 130 mm is used to study the effect of lightweight concrete only and a slab thickness of 150 mm is included to study the effect of different concrete type and different thickness. The lightweight concrete slab thickness of 150mm was selected to maintain the same self-weight as the normal concrete slab which had thickness of 130mm.

Table 1 shows a comparison of concrete thermal properties between NC and LC used in this study at ambient temperature. Mechanical properties of lightweight concrete are assumed to be similar to the normal concrete as mentioned in Section 2. The concrete temperature dependant properties are adopted in accordance with Eurocode EN 1994-1-2[38]. Figure 14 shows concrete slab temperature distribution. It can be seen that top surface of lightweight concrete has a lower temperature than that of normal concrete due to its lower thermal conductivity.

Table 1. Concrete thermal properties

Properties	NC	LC
Density (kg/m^3)	2300	2000
Specific heat (J/kg K)	1000	840
Thermal conductivity (W/mK)	1.6	1.0
Thermal expansion (°C^{-1})	13 x 10^{-6}	9 x 10^{-6}



a. Standard fire b. Natural fire

Figure 14: Temperature of concrete slab (thickness 130mm)

The predicted deflection at position P1, P2, and P3 between two different types of concrete with the same thickness 130 mm are plotted in Figure 15. The results show that using lightweight concrete produce slightly less deflection compared to with normal concrete. Although thermal expansion and self-weight of lightweight concrete are both less than that of normal concrete, their effect is insignificant on the global response of the composite floor. This is probably due to similar mechanical properties of both concrete types.

On the other hand, Figure 16 compares the deflection with the two different types of concrete and thicknesses. It shows that the lightweight concrete increases the failure time from 120 minutes to 150 minutes under the ISO standard fire. The comparison also shows that the effect of different concrete is negligible, up to 900C. At this point, the steel beams start losing strength and stiffness. With increasing temperature, the differences between the two slabs become more obvious. This is due to the fact that the role of concrete becomes significant in supporting the loads at high temperature. It can also be seen in Figure 16 the effect of the cooling phase in a Natural fire on the behaviour of the composite floor. The results show the recovery rates of deflection for both concrete slabs are similar. This indicates that the concrete cannot recover its strength and stiffness during the cooling phase. Hence, the unprotected secondary beams play an important role in the cooling phase.

Figure 17 shows the comparison of contour plots of the deflection pattern of structure with different concrete slabs when delamination has occurred. It can be clearly seen that the 150 mm lightweight concrete reduces the deflection and maintains the slab's deflected profile which follows a bowl-like shape i.e. 2-way action. This is due to the fact that the thicker slab can improve the vertical support of the perimeter beam in the slab panel. The steel reinforcement stress distribution (Figure 18) also shows that the 150 mm lightweight concrete slightly increases the mechanism of tensile membrane action. The analyses above demonstrated that using lightweight concrete with a thicker slab can improve the fire resistance of the composite floor at high temperature and confirms that the presence of the concrete slab must be considered in the analysis.

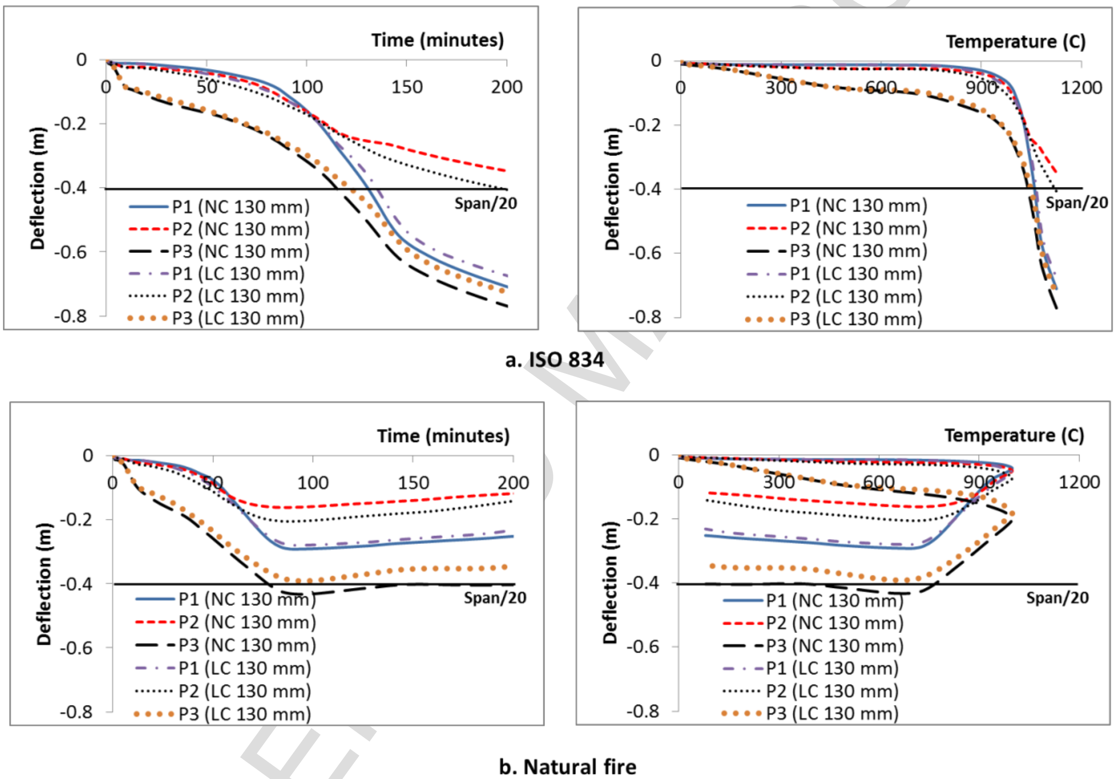
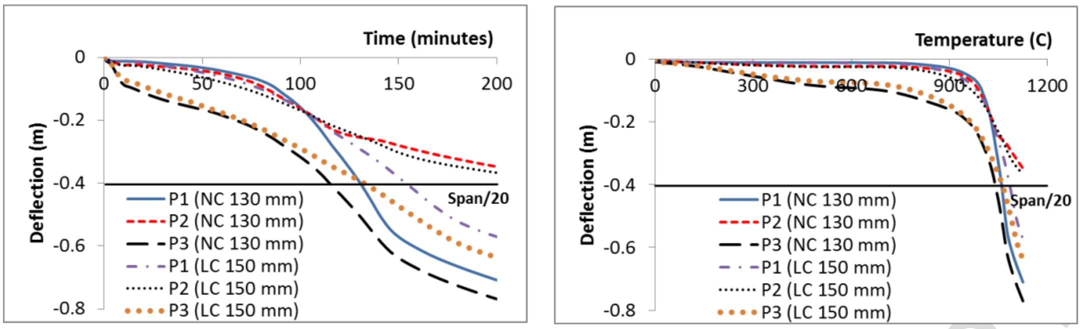
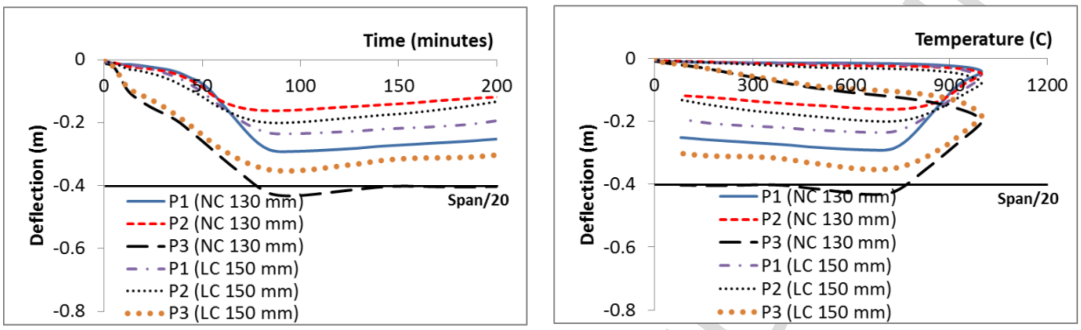


Figure 15: Predicted deflection at different positions using two different types of concrete slab



a. ISO 834



b. Natural fire

Figure 16: Predicted deflection at different positions using two different types of concrete slab and thickness

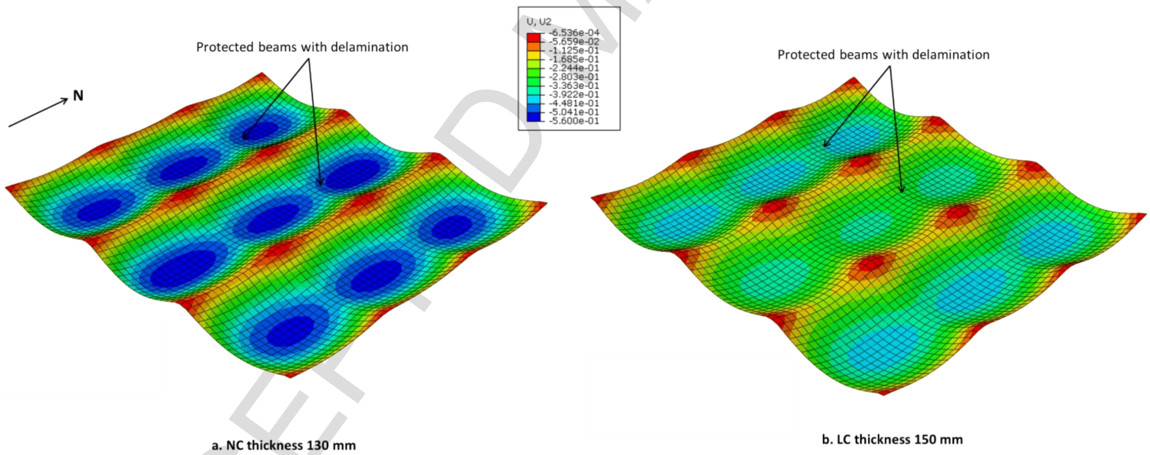
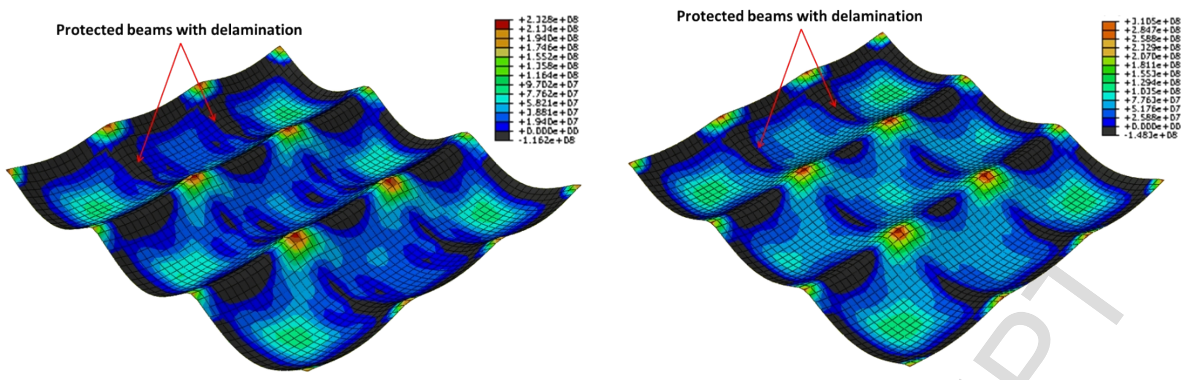


Figure 17: Deflected slab contour with fire insulation delamination using two different types of concrete slab after 120 minutes exposure to ISO standard fire (units in m)



a. NC thickness 130 mm

a. LC thickness 150 mm

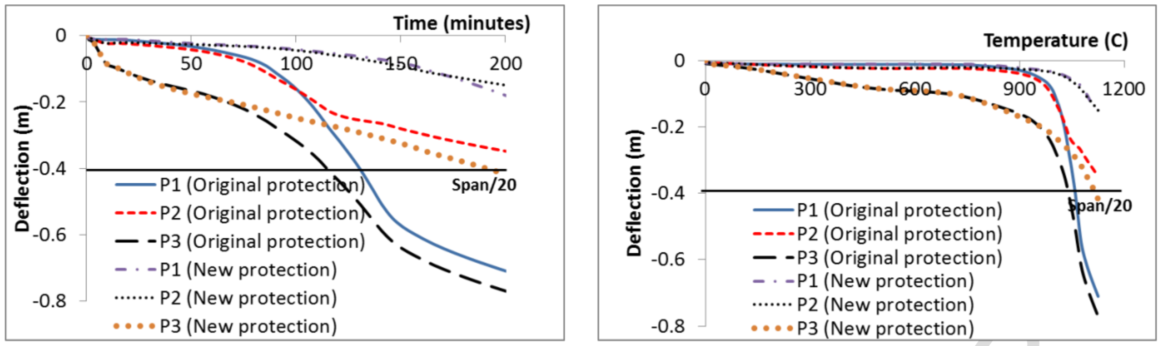
Figure 18: Maximum in-plane stress in the steel reinforcement layer for the slabs with fire insulation delamination using two different types of concrete after 120 minutes exposure to ISO standard fire (units in N/m^2)

6.2 Improving fire protection rating

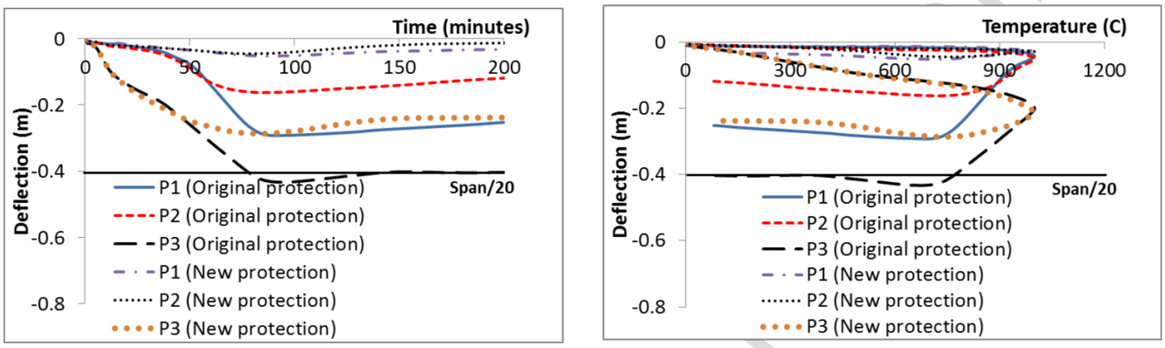
As indicated by the results in the previous section, the vertical deflection of protected beams at the perimeter of slab panels has significant influence on the formation of tensile membrane action. In this study, the new fire protection rating is applied to protected beams at the perimeter of slab panels to reduce the maximum temperature at the protected beam. The temperatures of the protected beams using the new fire protection are assumed to be 75% of those of the original fire protection, which is shown in Figure 6. The influences of the new fire protection application are investigated.

Figure 19 shows a comparison of the results of the mid-span protected primary beam, P1, P2 and P3 using both fire protection types. As expected, the influence of fire protection rating is very significant. With lower temperature, the deflections at the protected beams (P1 and P2) are drastically reduced. Tensile membrane action is considered to be still mobilised and increases the fire resistance of the slab from 120 minutes to nearly 200 minutes under the ISO standard fire. For the Natural fire case, the mid-span deflection of the slab is still within the limit.

Deflections at different positions under the ISO standard fire and natural fire when delamination has occurred are presented in Figure 20. In general, the behaviour of the protected beam with the new fire protection is similar to those of the original fire protection as discussed in Section 5.2. Sudden increase in deflection of P1 occurs when the delamination region reaches a temperature of 400°C. However, the deflections using the new fire protection are relatively small or only half of that of the original fire protection. Therefore, the tensile membrane action mechanism is considerably mobilised when the new enhanced fire protection is used as shown in Figure 21. It is also confirmed by the steel reinforcement stress (see Figure 22). It can be seen that with new fire protection compressive rings can fully form at the perimeter of the slab panel, even though fire insulation delamination occurs. It is clear from the analysis that limiting temperatures on the perimeter protected beams can prevent run-away failure of the structure at high temperature even if fire insulation delamination occurred at the ends of the protected beam.

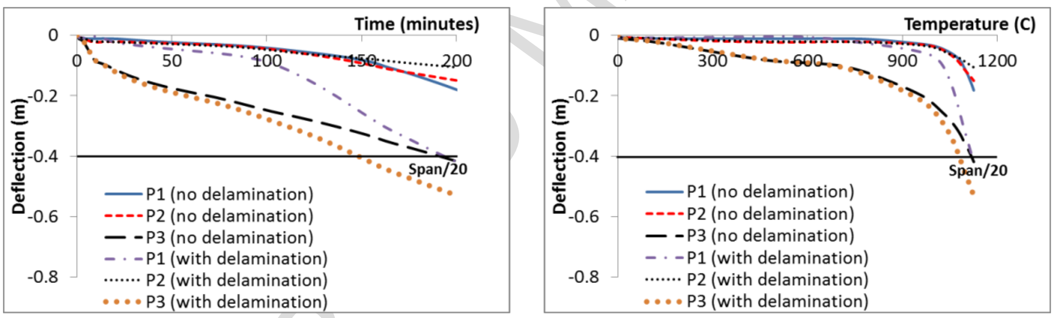


a. ISO 834

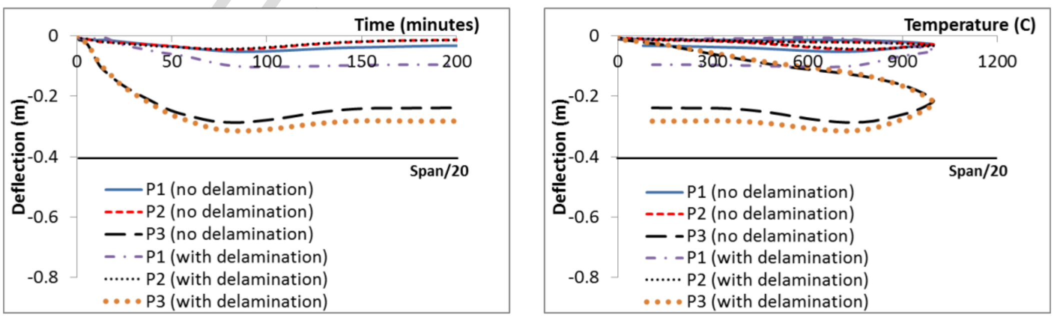


b. Natural fire

Figure 19: Predicted deflection at different points with different fire protection



a. ISO 834



b. Natural fire

Figure 20: Predicted deflection at different points using new fire protection

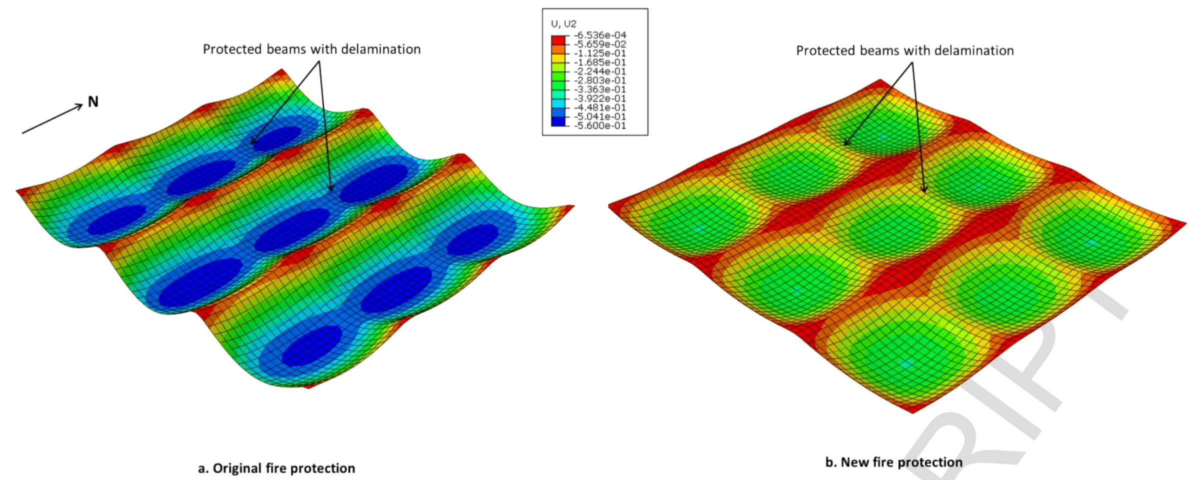


Figure 21: Deflected slab contour with fire insulation delamination using different types of fire protection exposed to ISO standard fire (units in m)

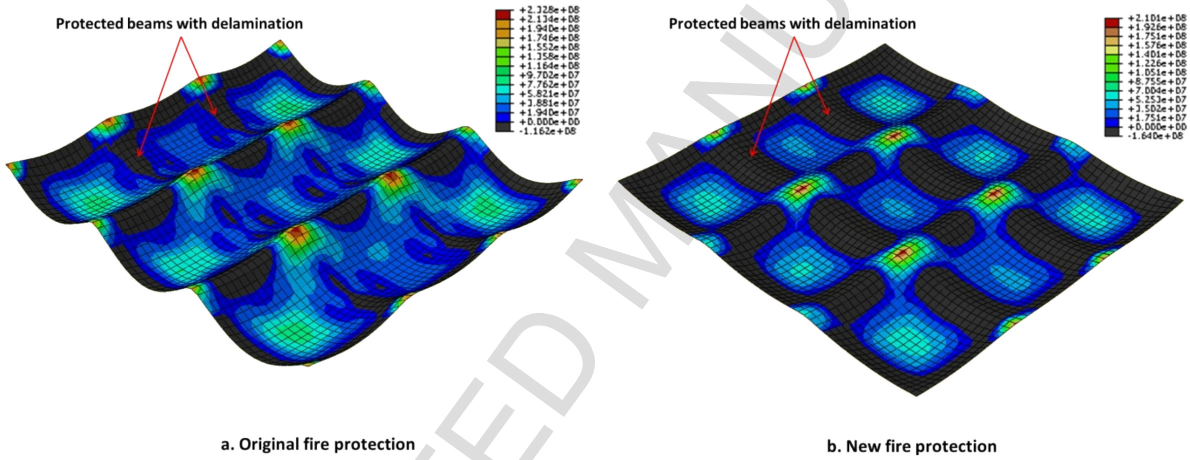


Figure 22 Maximum in-plane stress in the steel reinforcement layer for slabs with fire insulation delamination using different types of fire protection exposed to ISO standard fire (units in Nm^2)

7. Design recommendations

As previously mentioned, the provision of vertical supports along the slab panels plays an important role in the formation of tensile membrane action within the composite floor slabs at high temperature. At normal ambient temperature conditions, the loads within the floor slab initially supported by secondary beams will be transferred to the primary beams via one-way spanning floor slab action. Under fire conditions, when unprotected beams lose strength and stiffness, the tensile membrane action will develop within the floor slab and the slab becomes two-way spanning (see Figure 1). The tensile membrane action can enhance the load carrying capacity of the floor slab and is often relied on in fire situations. The main recommendation from the present study is: to safely use the benefit of tensile membrane action, the designer should make sure that vertical supports along the edge of slab panels are maintained particularly when fire protection delamination occurs in the protected beams.

The numerical studies described above show that fire insulation delamination on the protected beam can increase the deflection under fire following an earthquake. If the protected beams undergo excessive deformation, the floor slabs may begin to exhibit one-way spanning deformation, which will reduce the benefit of tensile membrane action. This has significant impact on the design since the benefits of tensile membrane action are commonly used for the performance-based fire design of composite buildings. Therefore, it is necessary to adopt strategies to prevent fire insulation delamination in the critical regions (plastic hinge regions). As an alternative solution, fire insulation delamination can be mitigated by using special types of insulation less prone to delamination. Zhang and Li [39] introduced a fire-resistive engineered cementitious composite (FR-ECC) to enhance the durability (adhesion and cohesion) of fire insulation. The study confirmed that FR-ECC can improve the adhesion energy by up to 6 times that of conventional SFRM.

To address the consequences of fire insulation delamination, this study investigated the most effective and practical ways to enhance fire resistance of composite floors. Improving the remaining fire protection rating can be considered as the most effective method to enhance fire resistance of the composite floor system. It can be achieved by increasing the fire protection thickness or reducing the thermal conductivity of the fire protection. The results above have shown that beams with the new enhanced fire protection can provide sufficient support to generate tensile membrane action (See Figure 22) when fire insulation delamination has occurred on the beams along the perimeter of the slab panel. However, the use of enhanced fire protection on the steel members may be a distinct disadvantage due to the extra cost and time to apply the protection. Another interesting alternative is application of lightweight concrete. Although lightweight concrete has the advantages of reduced self-weight and favourable thermal expansion properties, its effect on the fire resistance of the composite floor when compared with the same depth of normal concrete was negligible. However, using thicker lightweight concrete (giving an equivalent self-weight to the thinner normal concrete slab) can enhance the performance of the composite floor subjected to fire. Thus lightweight concrete can in this scenario offer a viable alternative to the use of enhanced fire protection on the steelwork.

8. Conclusions

This paper has presented a parametric study on a three-dimensional composite building, to investigate the effect of fire insulation delamination of protected beams on the development of tensile membrane action at high temperature. Two different methods, using lightweight concrete and improving fire protection rating, were also investigated as a means of improving the fire resistance of the composite slab where fire insulation delamination occurs. Based on the generic frame examined here, the following conclusions can be drawn from the results of this investigation:

1. In performance-based design for fire after earthquake conditions, three-dimensional modelling of composite frames is essential in order to identify the benefits of tensile membrane action. The tensile membrane action can significantly increase the load-carrying capacity above that estimated assuming flexural behaviour.
2. Fire insulation delamination can reduce the development of tensile membrane action and accelerate the failure of composite buildings due to catenary action of the beams being lost. This is due to the fact that fire insulation delamination increases vertical deflection of the protected beam which can subsequently change the load transfer mechanism from two-way into one-way slab behaviour.

3. Therefore, in seismic regions, protected edge beams should be designed to have adequate strength and stiffness in order to utilise the benefit of tensile membrane action even when fire insulation delamination occurs. The main requirement in order for tensile membrane action to be utilised is to maintain the vertical support along the perimeter of slab panels.
4. At high temperature, unprotected secondary beams lose their strength and stiffness significantly, resulting in loads being predominantly carried by the concrete floor slab. In this case, the concrete plays a more important role in affecting the fire resistance of the composite building. Therefore, using a thicker lightweight concrete slab can enhance the performance of a composite floor under fire.
5. Reducing the maximum steel temperature by 25% through the use of a fire protection with improved insulation rating can reduce the deflection to half of that with the original fire protection. Therefore, the tensile membrane action mechanism can be fully mobilised even when local fire insulation delamination occurs.

The generic frame geometry studied here was chosen to represent spans and service loading common in practice. Similarly, the study has focussed on a particular level of fire-protection delamination. The present work could be extended to examine alternative frame geometry and delamination scenarios. Further scenarios whereby significant seismically induced residual deformations are present in combination with delamination of protection could be explored. These issues are part of the authors' ongoing research.

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Conflict of Interest:

None declared.

Ethical Statement:
Authors state that the research was conducted according to ethical standards

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Improving the performance of composite floors subjected to post-earthquake fire

Highlights

- Three-dimensional modelling of composite frames is essential in order to identify the benefits of tensile membrane action.
- Fire insulation delamination can reduce the development of tensile membrane action and accelerate the failure of composite buildings
- Protected edge beams should be designed to have adequate strength and stiffness in order to utilise the benefit of tensile membrane action even when fire insulation delamination occurs.
- At high temperature, unprotected secondary beams lose their strength and stiffness significantly, resulting in loads being predominantly carried by the concrete floor slab.
- Reducing the maximum steel temperature by 25% through the use of a fire protection with improved insulation rating can reduce the deflection to half of that with the original fire protection even when local fire insulation delamination occurs.